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14. ABSTRACT

An in-depth analysis of the uncertainties associated with small-scale rocket engine testing has been conducted. The analysis uses terminology and approaches detailed in the ISO *'Guide to the Expression of Uncertainty in Measurement'* (GUM) and a recent NASA handbook on the subject (NASA HBK-8739.19-3). Along with this analysis, best practices for minimizing uncertainties are provided. AFRL's Experimental Cell-1 facility is used as the example engine, and the data values provided come from this system. The facility is sized to test a single, full-scale element or an array of scaled-down elements producing thrust in the range of 100-500 pounds. The facility has recently completed an overhaul to increase the number of data channels available and to improve accuracy. The measurand being specifically evaluated is c*-efficiency (η_{c*}). However, details are given on all of the parameters which contribute to the measurement and calculation of this value. This analysis should aid in the design, upgrade, operation and data assessment of EC-1 and other small-scale facilities.

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ACCURACY AND BEST PRACTICES FOR SMALL-SCALE ROCKET ENGINE TESTING

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Background

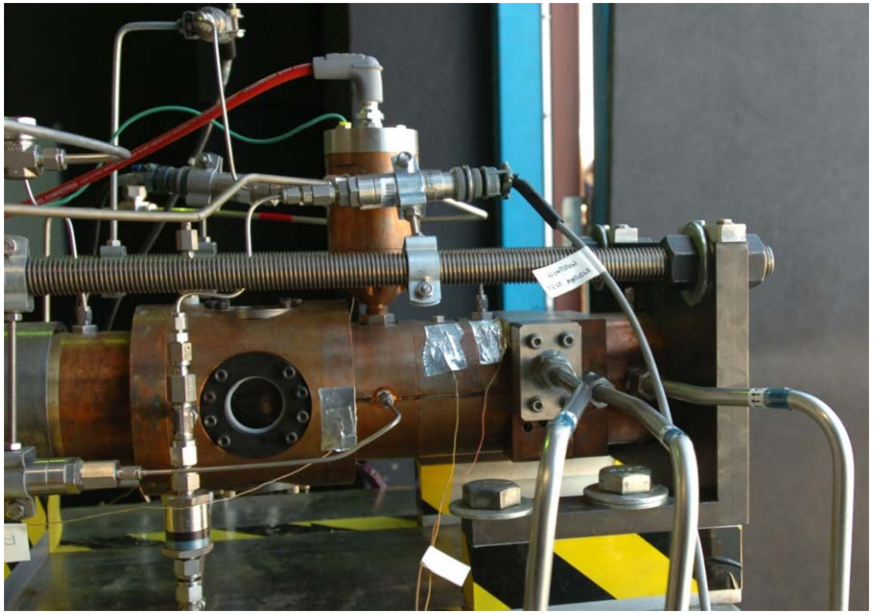
- **Metrology and uncertainty analysis has been through many updates in the last decade**
  - Guidance from ISO, NIST, NASA and AIAA in last 5 years
- **Rarely are complete, in-depth uncertainty analyses conducted for rocket engine measurements**
  - Comparing changes in fuel or hardware necessitates a strong understanding of uncertainties
  - Additionally, most journals require some analysis for publication (rarely is it complete or in-depth, however)
- **Recent upgrades in Edwards' EC-1 small-scale test facilities have utilized an involved analysis**
  - Best-practices were developed to lower uncertainty
  - Process upgrades continue as the analysis gets more in-depth
- **Here the best-practices and their reasons are presented**

Metric of Interest

- **Many parameters of interest could be used as a metric in the uncertainty analysis of a small-scale facility**
- **c*-efficiency is chosen here because of its utility for a variety of changes (fuel, injector, cooling, etc.)**
  - Measured c* is $P_c A_t / \dot{m}_{total}$
  - Theoretical c* is calculated using CEA code with rocket selection and finite chamber area option
    - CEA inputs are mixture ratio, area ratio (chamber to throat), formulation of hydrocarbon (C_xH_y), enthalpy of formation of hydrocarbon, chamber pressure and reactant temperature
- **Each input to the measured and theoretical c* will be discussed in terms of best practices and minimizing uncertainty**
  - Includes dependent measurements such as density and vapor pressure

Very Quick EC-1 Overview

- **EC-1 facility is a small-scale engine test rig**
  - Typically between 100-500 lb thrust
  - Heat-sink oxygen-free copper hardware
    - Heat losses and their accompanying uncertainties are NOT considered yet
  - GOX and liquid hydrocarbon considered here
    - Also can run with gaseous hydrogen or gaseous hydrocarbon



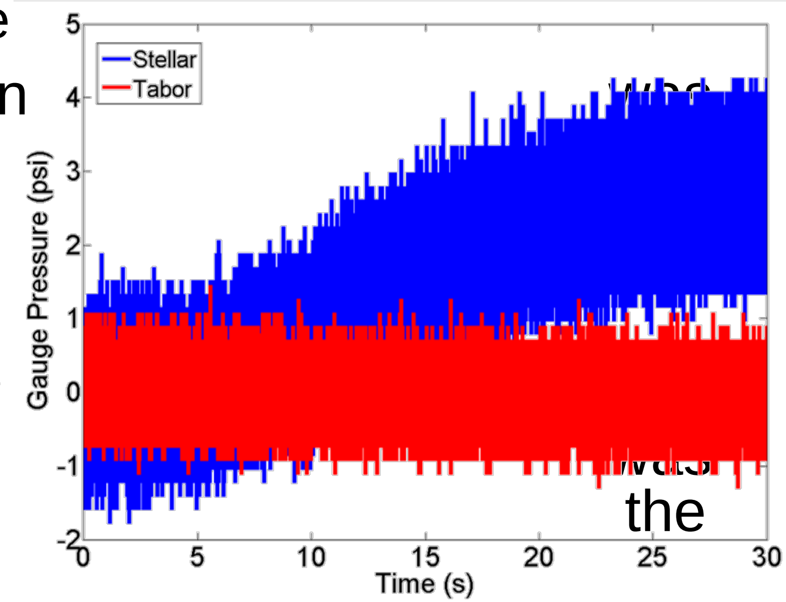
Weighted Least Squares

- **For most calibrations, a line is fit to the calibration points**
  - The method used can be quite important for determining uncertainty associated with linearity and hysteresis
- **Simple least squares methods do not use or produce information on uncertainties**
- **Weighted least squares methods can use uncertainty inputs and calculate uncertainties in the curve fit**
  - A good method will consider uncertainty in both the supplied and measured values
  - A good method will not assume these two uncertainties are identical
  - A good method will allow uncertainties to be different at each point

E. Mathioulakis and V. Belessiotis, *Uncertainty and Traceability in Calibration by Comparison, vol. 11, no. pp 771-775, 2000.*

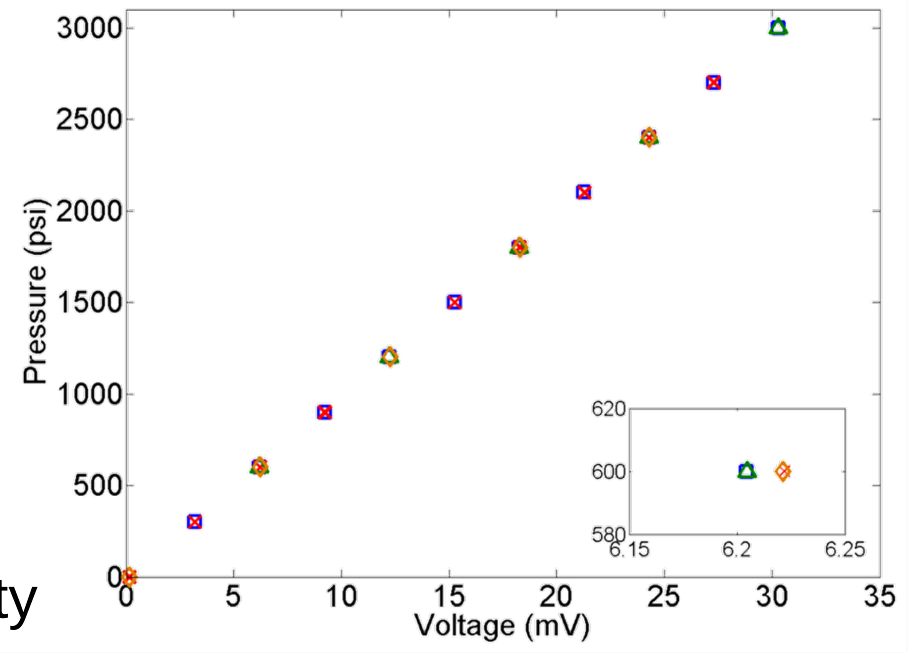
Pressure

- **Selection of high-quality transducers is imperative, but not always easy to assure**
- **Several problems were encountered with one manufacturer but not with another manufacturer**
  - Female bodies had zero point changes if fitting was tightened
    - EC-1 moved to male bodies on older transducers; new transducers do not have this issue
  - Internal temperature compensation not effective
    - EC-1 moved to uncompensated transducers which will be calibrated using an oven to develop temperature-dependence
  - Manufacturer given uncertainty not the actual uncertainty of the transducer
    - Calibration is a must to determine actual uncertainty esp. linearity and hysteresis for a specific transducer



Pressure

- **Routine calibration of transducers is required**
  - Prior analysis should be used to assure transducers remain within the uncertainty and uncertainty should be enlarged if the calibration period was too long
  - EC-1 calibrates following every series of tests (e.g., when an injector is changed)
  - A series of upward and downward cycles is needed to elucidate the hysteresis of the system and ensure its inclusion in the uncertainty
  - Currently, the linearity and hysteresis of the transducers is the largest component of the uncertainty



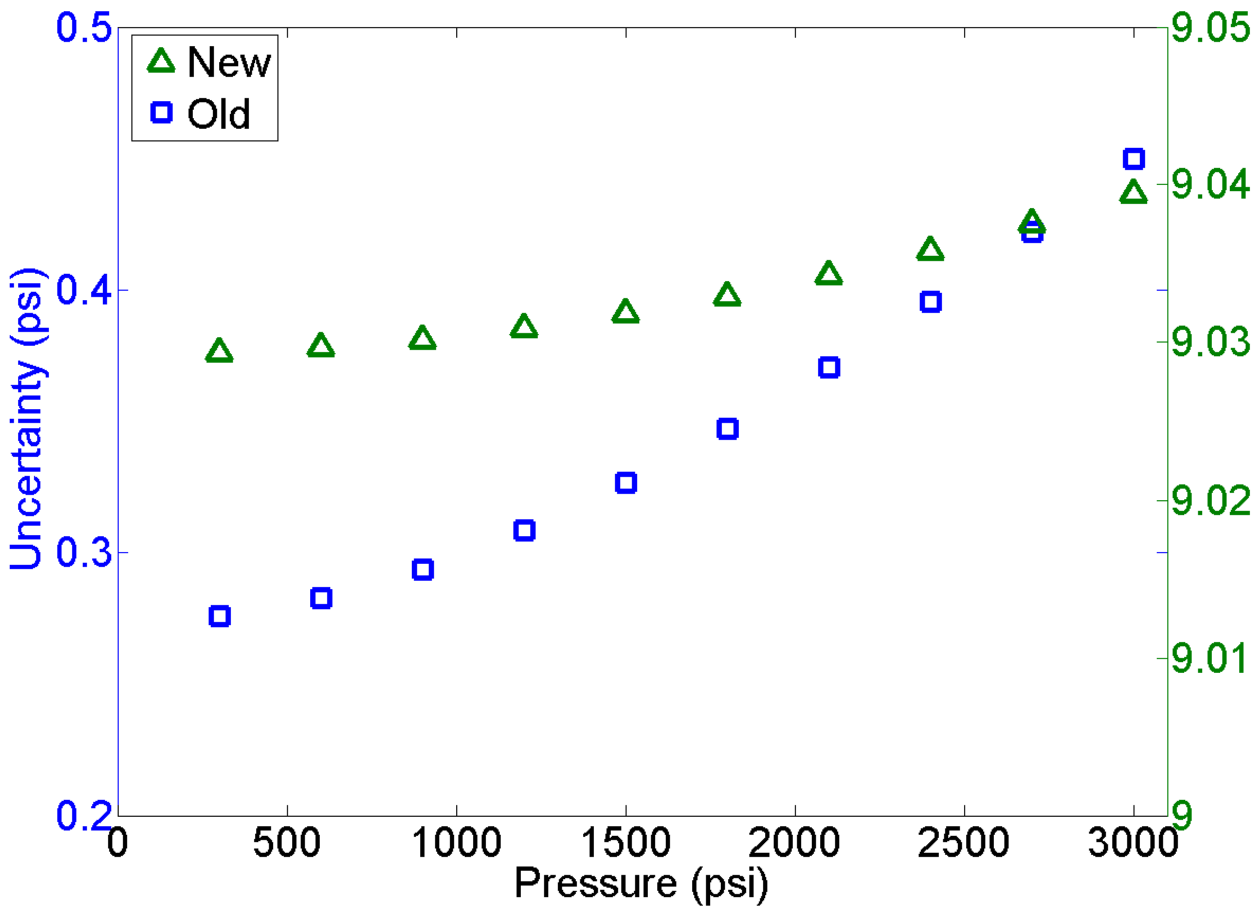
Pressure

- **Match the transducer to the range being recorded**
  – Using a 0-3000 psi transducer to measure atmospheric pressure might give a reading of 14 +/- 1 psi while a 0-15 psi transducer with a similar % uncertainty would give a 13.72 +/- 0.015 psi reading
- **Atmospheric pressure should be recorded daily at minimum, but during the test is better**
  – Reduces uncertainty in absolute pressure used in the c* calculations
- **Snubbing with a low density gas is recommended**
  – Failing this, long leads and periodic inspection are required to ensure heat, soot and unburned hydrocarbons have not damaged the transducers
  – Helps insulate transducer from soot and hydrocarbons
  – Reduces time constant even with reasonably long leads
- **Proper grounding and shielding of wires is crucial**

Pressure

- **Chopping power supplies (regulators) in amplified transducers creates oscillatory output**
  - Several transducer manufacturers were tried, all exhibited the same issue
  - Issue can be measured with oscilloscope or, depending on DAQ system, may be visible in output or supplied power
- **Oscillations feed back to the supply system and other transducers**
- **EC-1 now uses unamplified transducers**
- **Additionally, power is supplied via DAQ (Pacific Instruments 60-32-EM card) so at most 4 transducers are powered together**
- **With changes, no oscillatory behavior is observed and standard deviation in voltage is substantially decreased**

Pressure



Two randomly selected transducers. New transducers are unamplified; old are amplified

Temperature

- **Temperature enters directly in CEA input along with being a dependent variable in both flow rates**
- **A known junction temperature, through the use of a junction box, lowers uncertainty**
  - EC-1 uses a hot junction box because the experimental cell is not climate controlled (kept at 150°F)
- **Wire length should be kept to a practical minimum**
  - Reduces cost—thermocouple grade wire should be used even on short distances
  - Reduces resistivity of wire (shorter lengths recommended by manufacturer)
  - Reduces noise due to electromagnetic background
    - Wires should be properly shielded and the system should be properly grounded

Temperature

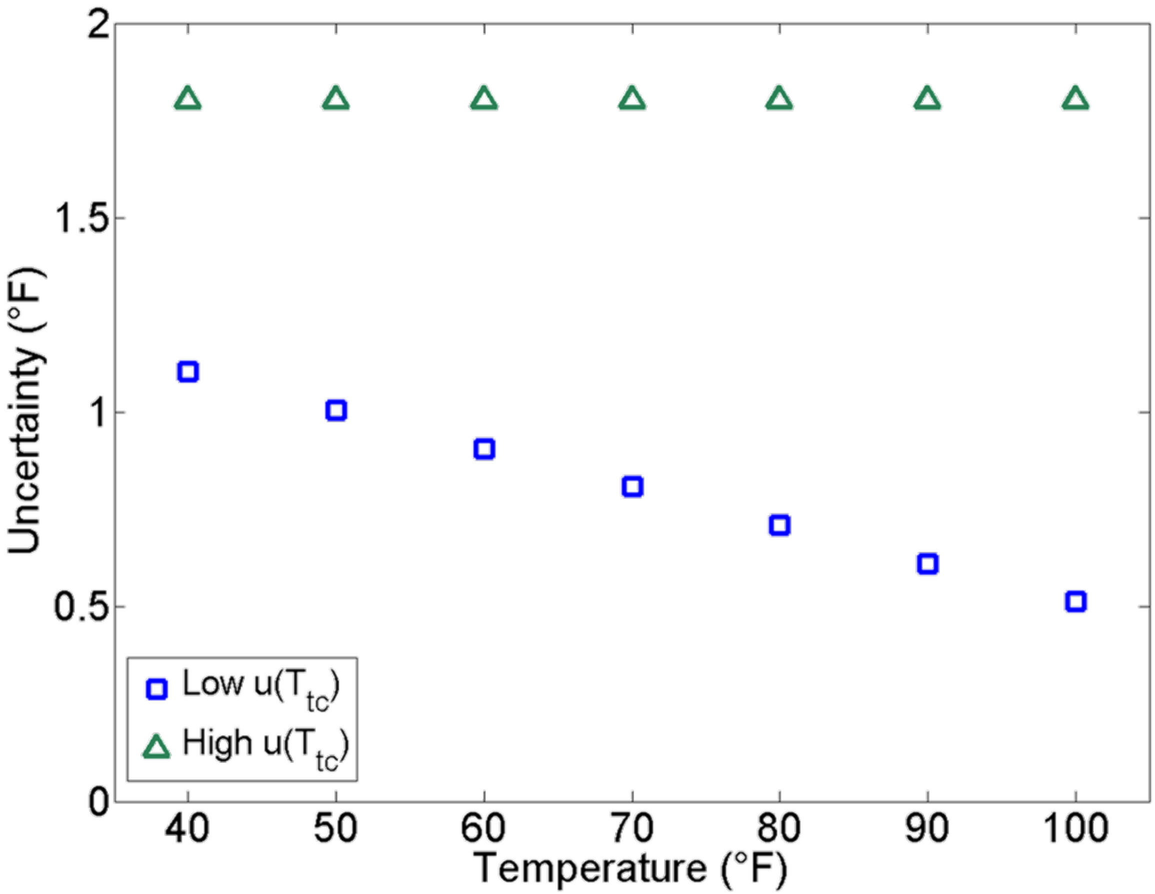
- **For full analysis, channels should be calibrated in situ using a thermocouple simulator**
  – Alternately, each component in the system could be calibrated separately versus an in-situ system calibration
    - Obviously, this is time consuming
    - It assumes no feedback from any components to other components
  – If wire lengths, junction box, etc are the same then a few channels can be calibrated and the others verified at one or two points
  – While small, the noise in the system may not be negligible so, at a bare minimum, a few channels should be verified at two points to ensure uncertainty is at expected levels
  – EC-1 calibrated 5 randomly selected (in-use) channels yearly and verifies all channels prior to placing them in service

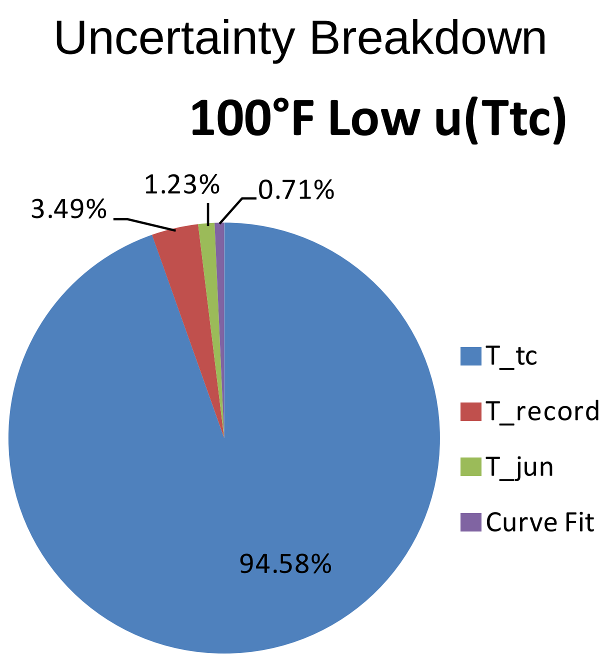
Temperature

- **Uncertainty in thermocouple itself is currently the largest contributor to combined uncertainty**
  - EC-1 currently relies on manufacturer's provided uncertainty values and verifies a thermocouple in each batch is within the given uncertainty
  - Thermocouples should be calibrated; some percentage are likely to have lower-than-cited uncertainty
  - Selection of thermocouple type can be important
    - Balance between cost and accuracy
    - Match expected range and thermocouple within the available budget
    - EC-1 uses Type E thermocouples to measure propellant temperatures and Type K to measure engine wall temperatures

Temperature

- **Low uncertainty thermocouple is 1% of difference between the thermocouple junction and reference**
- **High uncertainty thermocouple is 1°C**





Areas (Throat)

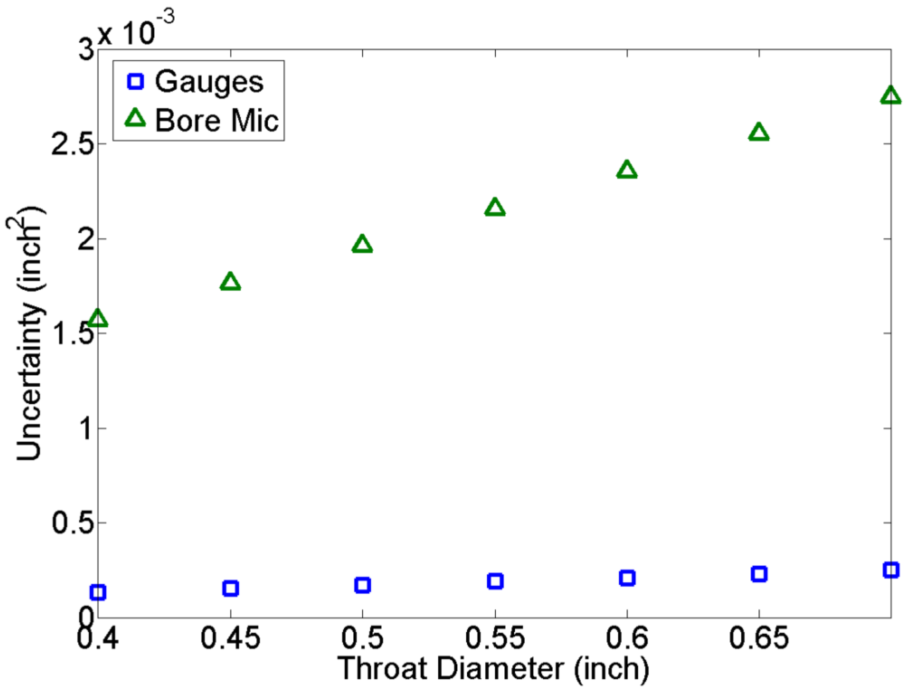
- **Throat diameter is measured using pin gauges**
  - Reduces user-to-user variation versus bore micrometer
  - Black oxide coating allows visual inspection instead of frequent calibration
  - Smallest increments commercially available ($5x10^{-4}$ inch)
  - Not temperature controlled or monitored (this introduces a reasonable additional uncertainty)
  - Main contributor to uncertainty is resolution (increments available) and user bias (strong function of resolution)
- **Circularity of the nozzle is assumed**
  - Not verified in a rigorous manner
  - Requires careful nozzle design
- **Changes during firing are also ignored**
  - Variation after run MUST be added to uncertainty
  - Changes from run-to-run indicate need to redesign nozzle cooling to lower uncertainty

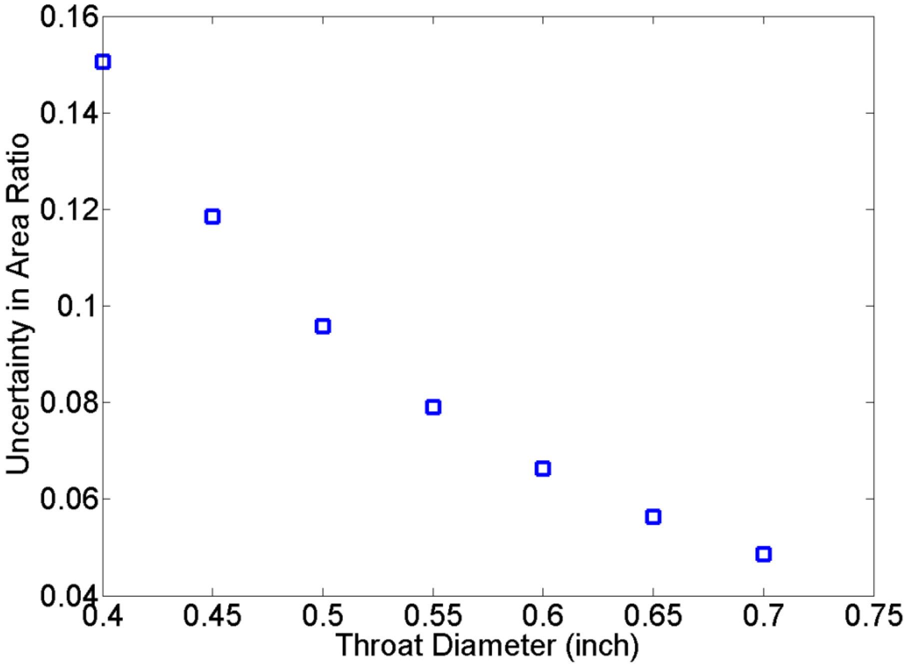
Areas (Chamber)

- **Chamber is typically 2 inches square with ¼ inch radii at the corners**
  - Rounded corners should be included in area calculation (were neglected in early EC-1 testing)
- **Dimensions should be measured before and after each series of runs**
  - Currently, EC-1 uses engineering tolerances for the uncertainty analysis
  - A program to implement this recommendation and augment uncertainty accordingly is underway
- **As with the nozzle area, changes during the experiment are neglected**
  - No way to measure these changes
  - Heat-sink hardware makes this unlikely to be true, so appropriate additions to uncertainty are being considered

Areas

- **Area Ratio uncertainty is 0.55% of the ratio (area ratios of 9 to 27 investigated)**
- **The uncertainty in chamber area dominates the area ratio uncertainty**
  - Currently, this uncertainty is unrealistically low as cited on previous slide





Liquid Mass Flow Rate

- **The analysis assumes a liquid fuel and gaseous oxidizer as this is typical in EC-1**
- **Liquid flow is metered using a cavitating venturi**
- **Density and vapor pressure are important components in calculating the flow rate**
  - Unless the fuel is a single, well-known chemical, they should be measured for each batch of fuel used
  - ASTM standards (D4052, D6377) should be used
  - Unless provisions are taken to control fuel temperature upstream of the venturi, measurements should be made as a function of temperature
  - Temperature enters the flow calculations through these properties
- **Pressure is the other dependent variable and was addressed earlier**

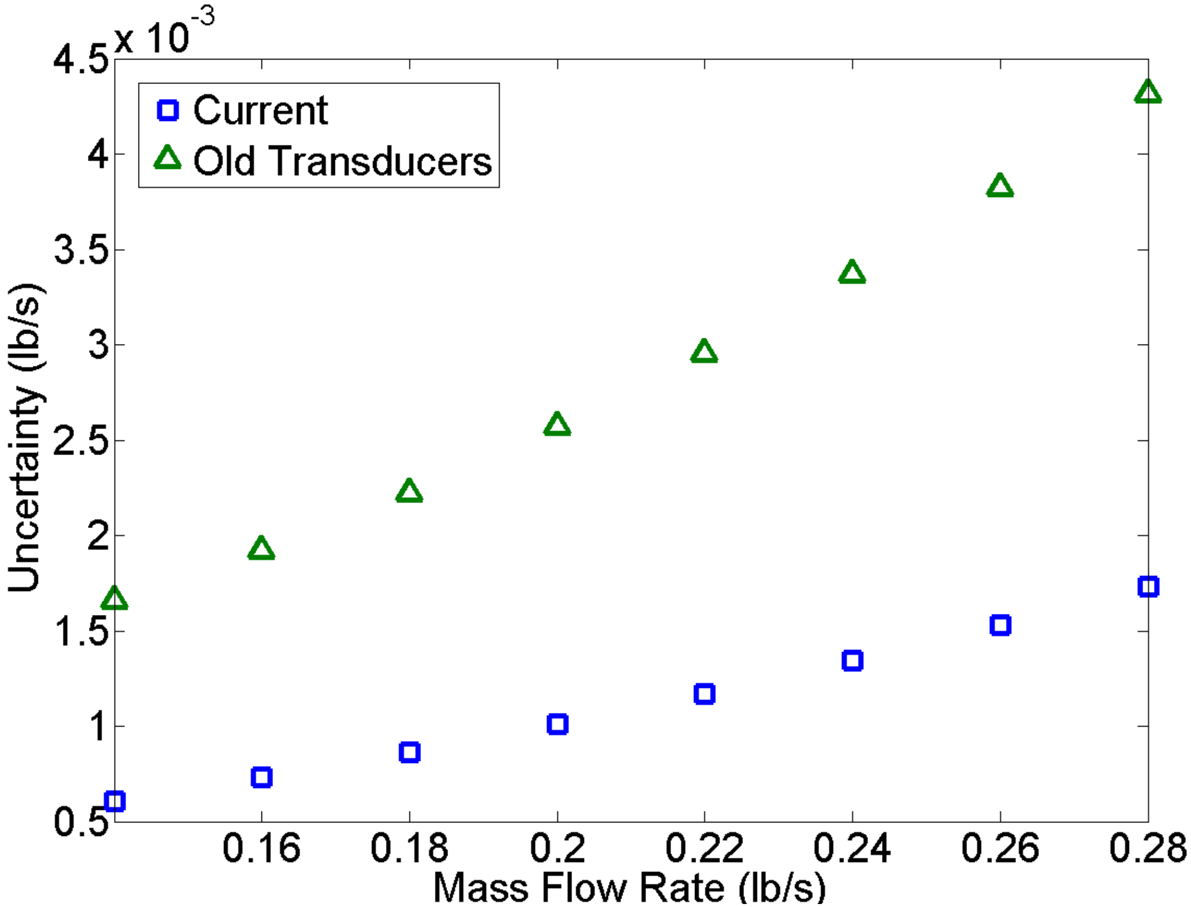
Liquid Flow Rate

- **Discharge coefficients should be calibrated at least yearly (and spot-checked after periods of heavy use)**
  - Do not measure throat diameter and set a discharge coefficient as this adds <u>substantial</u> uncertainty
  - Calibrate using the actual fuels if practical; calibrate in the test system if practical
    - Reduces uncertainty substantially
  - Catch-and-weigh is generally the easiest calibration to employ and can be quite accurate
    - Use as large a time and weight as can be practically managed
  - EC-1 calibrated yearly in this manner
    - Actual fuels are used unless highly volatile or small quantity availability
    - Water calibrations are also performed (used for spot-checks between calibrations)
    - C_D has been observed to change on the order of 0.5% yearly

Liquid Flow Rates

- **Sufficient upstream and downstream distances must be provided to obtain developed, not swirling flow**
  - EC-1 has >20D upstream and >13D downstream
  - Minimum industry recommendations are 10D upstream and 5D downstream
  - Can be relaxed if calibrating in the test system; however, discharge coefficient will likely be function of pressure
- **Effects of dissolved gases were examined and found to be unmeasurable in EC-1 system**
  - However, bubbly flow downstream is undesirable for other reasons so bladder tanks are used
  - Fuel is not degassed prior to use
- **Vapor pressure and discharge coefficient uncertainties currently dominate**
  - Prior to improvements, pressure uncertainty was a large contributor

Liquid Flow Rate



- **The current uncertainty in liquid flow rate contrasted with the uncertainty with the current set-up except a change to the amplified transducers**

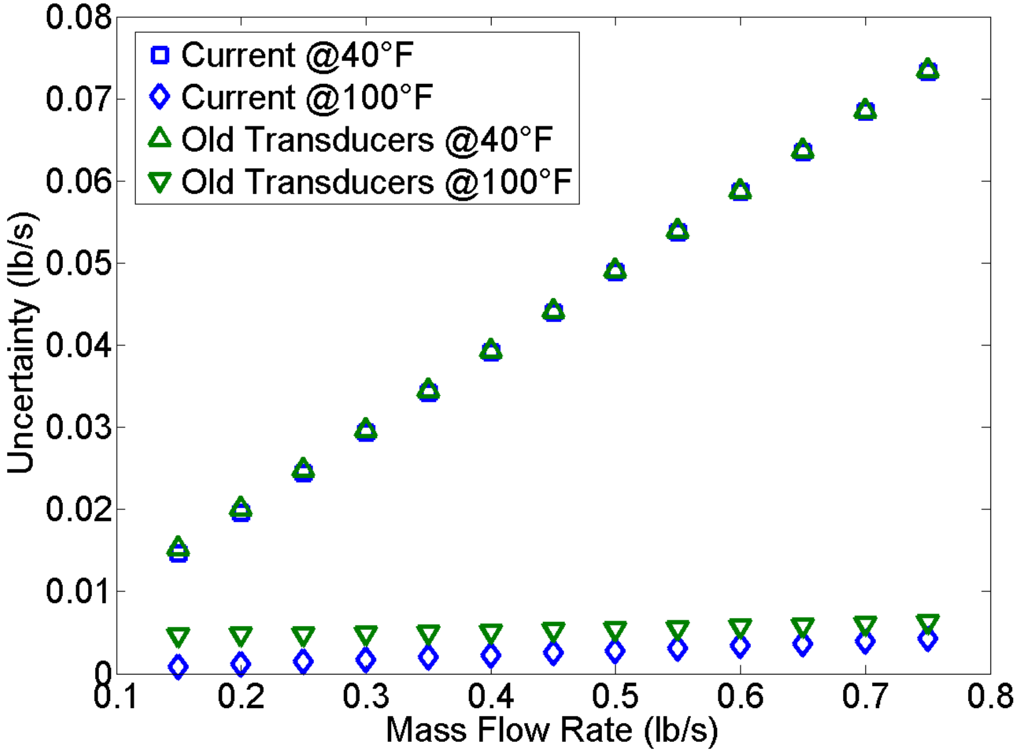
Gas Flow Rate

- **Gas flow is metered using a sonic nozzle**
- **Dependent on pressure and temperature**
- **As with liquid flow rate, calibrate to get C_D**
  - Measuring area and assuming discharge coefficient results in higher uncertainty
  - Discharge coefficients show less change over time than the venturis (still has some change)
  - Calibrations have been done at CEESI and in-line using a CEESI-calibrated nozzle upstream
    - Previously, a catch-and-weigh setup has been used but its complexity and specialized equipment made it undesirable since it did not produce lower uncertainties
  - EC-1 recalibrates in-house yearly or after heavy use

Gas Flow Rate

- **Use an established procedure to calculate critical flow factor for the measured temperature and pressure**
  - Several published procedures with similar, very small uncertainties (EC-1 uses a procedure by Stewart, Watson and Vaidya)
  - For large throat-to-pipe ratios this should be corrected for the finite velocity upstream of the throat
- **Provide sufficient upstream and downstream distances to have fully developed, not swirling flow**
  - EC-1 has >28D upstream and 13.5D downstream
- **Locate valves downstream to mitigate compression upstream of the throat**
  - Otherwise a nearly step-wise change in temperature overwhelms the thermocouple and may prevent reliable temperature readings

Gas Flow Rates



- **Combined uncertainty is a larger percentage of flow rate than that in the liquid (dominates uncertainty in mixture ratio and total mass flow)**
- **Combined uncertainty has a strong dependence on the uncertainty in the temperature**

Stoichiometric Coefficients

- **CEA needs the formulation of the hydrocarbon as an input**
- **For single component fuels this is easy, but many liquid fuels are mixtures (such as RP-1 or RP-2)**
  - Measurements should be made for each batch of fuel
- **Use an ASTM method (given in standard D5291) to calculate the hydrogen and carbon percentage**
  - While contaminant levels are low for most fuels, the calculation should not rely on hydrogen percentage alone
    - Failure to know the contaminant level introduces substantial additional uncertainty
    - Carbon percentage is calculated by instruments at the same time a hydrogen percentage
- **Using a C_xH_1 formulation minimizes uncertainty in coefficients, but does not minimize uncertainty in enthalpy**

Enthalpy

- **Again, for multicomponent fuels the heat of combustion should be measured for every batch**
  - ASTM method D4809 is recommended
- **Enthalpy of formation is calculated from this heat of combustion along with other well-established values**
  - These include molecular weights and enthalpies of formation of water and carbon dioxide
- **C_1H_y formulation minimizes uncertainty in enthalpy**
  - This finding is in direct opposition to that of the stoichiometric coefficients
  - The sensitivity coefficients of the CEA code are needed to establish which formulation results in a lower combined uncertainty in theoretical c*
  - Calculations at a single operating condition indicate the C_1H_y formulations is the best choice

Theoretical c*

- **Analysis is based on a single point**
- **Rough sensitivity coefficient determination around that single point**
- **Mixture ratio dominates the combined uncertainty**
  - This finding is due in large part to its sensitivity
  - Mixture ratio uncertainty is dominated by uncertainty in gas flow rate which is, in turn, dominated by uncertainty in temperature
    - From this EC-1 has found it imperative to calibrate thermocouples prior to use
- **At single condition considered (MR=2.4, AR=21.4, Pc=700 psi, T=77°F) the uncertainty of 0.14% using the lowest thermocouple uncertainty (0.30% for other thermocouple manufacturer)**

Measured c*

- **Analysis based on a range of points but a single venturi and sonic nozzle**
  - Chamber pressures 300-1000 psi, Throat Diameters 0.45 to 0.65 inch, total mass flow rates 0.25-1.15 lb/s
- **Mass flow rate dominates the combined uncertainty**
  - Main component of the total mass flow rate uncertainty is the gas flow rate
  - Again, temperature is the major contributor
- **Dependent on temperatures, using the low uncertainty thermocouples, the combined uncertainty in c* could be as high as 7.6% or as low at 0.5%**
  - For a moderate (and typical) temperature of 70°F the uncertainty is <2%

c*-Efficiency

- **Only a single condition has been considered to date (m_{liq}=0.208 lb/s, m_{gas}=0.500 lb/s, AR=21.4, P_c=700 psi, T=77°F)**
- **Combined uncertainty at this condition is 1.22%**
  - Strongly driven by temperature uncertainty
  - Due to strong gas flow rate dependence, combined uncertainty is close to specific uncertainty in gas flow rate
    - This suggests that the range for 40-100°F may run from nearly 8% to under 1%
- **Updates to system have decreased uncertainty significantly**
  - At specific condition cited just changing transducers HALVED the uncertainty
  - Prior uncertainty was just under 3%
- **Does not include heat-loss corrections or uncertainties**

Future Work

- **Several items remain to further clarify uncertainty or to improve the combined uncertainty**
- **First and foremost, thermocouples will be calibrated!**
- **Heat transfer losses to the heat-sink hardware remain to be evaluated**
- **A more robust and throrough evaluation of the CEA code at the range of typical conditions**
- **On-going monitoring and assessment of engine cross sectional area is being implemented**
- **Determine temperature dependence of the pressure transducers through calibration in an oven**
- **Confidence bounds have not been established**
  - Unlikely that a 95% confidence bound will be a simple multiple of 2 (too few degrees of freedom)